Quantifying Uncertainty through Global and Mesoscale Ensembles

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LONG-TERM GOALS

The long-term goal of this project is to develop robust global and mesoscale ensemble analysis and forecast systems that are able to provide probabilistic forecast guidance in an operational environment. Although most operational centers rely solely on single deterministic forecasts from numerical weather prediction models, recent advances in probabilistic prediction, or ensemble forecasting, have made this a very powerful tool for providing more complete input on environmental conditions, including a measure of the forecast confidence. Since the atmosphere is inherently chaotic, the model predictions of most, if not all phenomena will always be sensitive to the model initial conditions and physical parameterizations. Mesoscale models are additionally constrained by potential errors inherent in the specification of the lateral boundary conditions (LBC). Due to these inevitable uncertainties, forecasts are most appropriately viewed in a probabilistic sense; that is, forecasts should provide probabilities of the occurrence of specific high-impact events, as well as estimates of forecast skill. Recent research at NRL and other research centers has demonstrated that probabilistic information can be obtained from ensemble of forecasts created from equally plausible initial states and equally-likely model formulations. However, such a probabilistic prediction of Navy relevant high-impact weather will significantly benefit sea strike and sea shield functions only if there are clearly identified *user-relevant* norms. For example, METOC impacts on operations are typically listed in a “stoplight” format, often with multiple weather criteria that must be satisfied (e.g., for the Predator, precipitation, winds, ceiling, visibility, cloud cover, icing, turbulence, and temperature). Probabilistic forecasts allow for a different probability threshold to be set for each criterion individually (e.g. a 90% probability for winds, but only a 70% probability for visibility), reflecting the relevant importance of each weather factor. Ensembles also allow for the covariance between relevant weather variables to be taken into account. In a particular instance, wind and visibility may have a wide range of values they might take on (broad probability distribution functions), but information in the covariance could tell you that *if* the wind speed is high, *then* visibility will also be high.

A prototype global Ensemble Transform (ET) ensemble system has been developed as part of research performed in recent NRL base projects on global modeling and predictability (Bishop and Toth 1999, McLay et al. 2007). In addition, a prototype ET mesoscale ensemble system, driven by this global ensemble, has been developed within the NRL 6.2 project "Probabilistic Prediction of High-Impact Weather" that was approved for FY06-FY09. The work in this NRL base project on mesoscale ensembles has been incorporated into this RTP project, and the funding for it, and the additional ONR and PMW-180 funding approved for this RTP, will allow for both the global and mesoscale ensemble systems to be more fully developed, tested, validated, and transitioned to operations during the time period of FY07-FY09.

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The long-term goal of this project is to develop robust global and mesoscale ensemble analysis and forecast systems that are able to provide probabilistic forecast guidance in an operational environment. Although most operational centers rely solely on single deterministic forecasts from numerical weather prediction models, recent advances in probabilistic prediction, or ensemble forecasting, have made this a very powerful tool for providing more complete input on environmental conditions, including a measure of the forecast confidence. Since the atmosphere is inherently chaotic, the model predictions of most, if not all phenomena will always be sensitive to the model initial conditions and physical parameterizations.

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OBJECTIVES

The objective of this project is to incrementally develop and test an integrated multi-scale ensemble modeling framework and forecasting system, and validate and transition it to operations at the Fleet Numerical Meteorology and Oceanography Center (FNMOC). This system will be a state of the art global and mesoscale ensemble forecasting system using the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled/Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]). It will incorporate consideration of uncertainty in the initial state (and lateral boundaries where appropriate) along with consideration of uncertainty in the model formulation. It will be a user-friendly, easily re-locatable system flexible enough to incorporate new advances in data assimilation and post-processing schemes. The system will provide high fidelity, dynamically consistent probabilistic forecasts, and estimates of forecast uncertainty for the battlespace environment. These global and mesoscale ensemble forecasts will lead to superior probabilistic weather forecasts that will directly improve tactical decision aids (TDA) for support of FORCENET and the Sea Power 21 pillars (Sea Basing, Sea Shield, and Sea Strike), and for applications to homeland security and the global war on terrorism (GWOT).

APPROACH

Our approach is to take existing prototype global and mesoscale ensemble forecast systems, built through current and previous NRL in-house funding, and incrementally develop these individual systems into an operationally feasible, next-generation, multi-scale ensemble prediction system. This system will consist of (a) the representation of initial and model uncertainty in NOGAPS, (b) the representation of initial, lateral boundary condition (LBC), and model uncertainty in COAMPS, (c) an integrated, robust global-mesoscale ensemble infrastructure (to ensure consistent perturbations between the global and mesoscale systems, result in improvements to the global system having an immediate impact on the mesoscale system, and promote ease of use), (d) an ensemble verification system, including scorecard, and (e) a demonstration of performance capabilities in an operational setting. The system will be thoroughly tested using scientific studies and norms and comprehensive ensemble forecast experiments.

WORK COMPLETED

For the development of the global ensemble system, a comparison between the new ET (Bishop and Toth 1999) and the previously operational Bred Vector (BV, Toth and Kalnay 1993) scheme has shown the ET scheme to be superior under many different metrics (McLay et al. 2008). The ET scheme was transitioned to FNMOC in March 2008. Research is now underway to improve the current fit of the initial perturbations to the analysis error variance estimates produced by the data assimilation scheme using an alternative basis (McLay and Reynolds 2008). Research also investigated the impact of combining the ET with stochastic convection (Teixeira and Reynolds 2007; Reynolds et al. 2008) including the impact on tropical cyclone track forecasts. Finally, ongoing research is examining how varying parameter values may be used as a way to include model uncertainty in ensemble design.

For the development of the mesoscale ensemble system, the new ET method for generating initial perturbations has also been implemented within COAMPS. Perturbed lateral boundary conditions to drive the ensemble were obtained from the global NOGAPS ET ensemble (McLay et al., 2007a, b). The 29-member COAMPS ensemble system has been tested by running it over a three week period for summer 2005. To quantitatively evaluate the performance of the mesoscale ensemble, a large suite of

diagnostics was developed and employed, as well as prototype post-processing software. A new, modified set of ensemble perturbations was developed, tested, and compared to the original set of perturbations. The testing of the ability of the multi-parameter ET ensemble to work with high resolution nests for the urban meteorology case over Tokyo at 1.67 km resolution using 11 members was extended to 21 members by including sea surface temperature (SST) perturbations. The initial technique to emulate a fully coupled air-ocean system was to use off-line COAMPS simulations to force an ocean model, and then force the atmospheric ensemble with the subsequent SST fields varying every hour.

RESULTS

While the first version of the global ET has already been transitioned to operations, there are still issues with the current ET implementation that merit further research. One issue is that the ET scheme has too little ensemble variance in the tropics when compared to the analysis error variance estimate that is produced by the operational data assimilation system. This is attributable, in part, to the fact that the 6-h ensemble forecast perturbations currently serving as the basis for the ensemble transform are too spatially localized. Recently, two alternative bases, one composed of prior 72-h ensemble forecasts (EXP1) and one composed of an archive of randomly-sampled ensemble forecasts (EXP2) have been compared with the operational basis currently being used (OPER). Results show both experiments give improved performance under a variety of metrics, including increased ensemble variance in the tropics and improved Brier scores (Fig. 1). This improved performance is attributable to the reduced localization in the experimental basis perturbations as compared to the operational perturbations (McLay and Reynolds 2008).

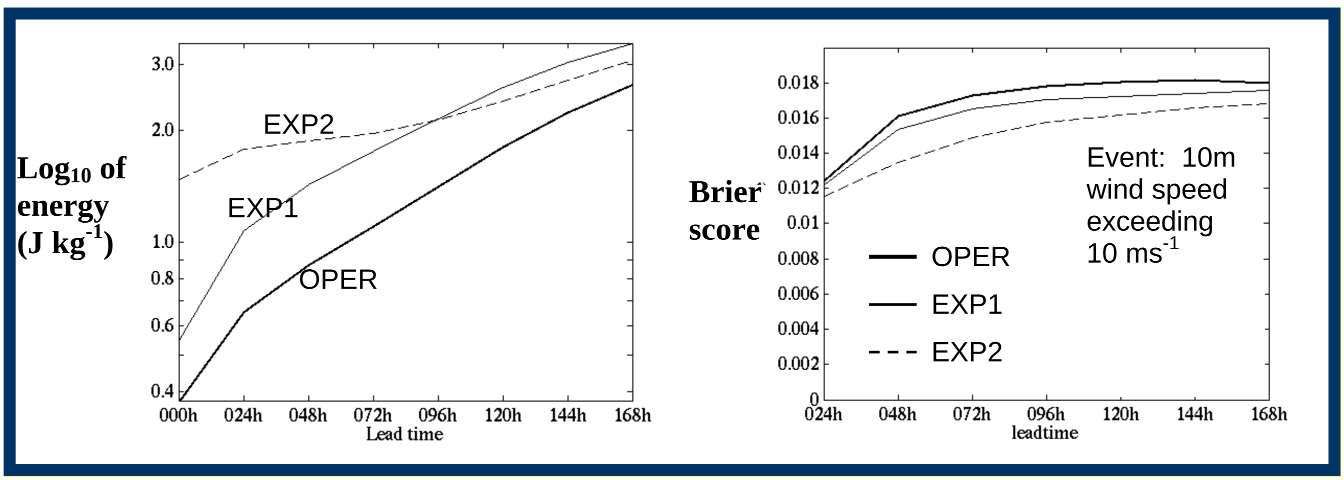

Fig. 1. Results for the operational version of the ET (thick solid curves) as compared with two experimental versions using alternative bases for NOGAPS forecasts in the tropics. The left panel shows ensemble variance as a function of forecast time in terms of total energy. The right panel shows Brier score (probabilistic forecast error score) as a function of forecast time for 10-m wind speed in the tropics exceeding 10 m s^{-1}.

Another way to improve the current ET implementation is through inclusion of model uncertainty. Experiments combining the ET with stochastic convection show improved ensemble performance under a variety of metrics in the tropics, with little impact in the extra-tropics (Reynolds et al. 2008).

It is shown that, because the ET is a cycling scheme, direct changes to the forecasts result in indirect changes to the initial perturbations as well. Improvements from the stochastic convection scheme are attributable to both direct and indirect changes at short forecast times, and primarily to the direct model changes at longer forecast times. The utility of the ET stochastic convection ensemble for tropical cyclone track forecasting has also been examined. It is found that, at forecast lead times beyond 72 hours, the ET with stochastic convection provides ensemble mean tropical cyclone track forecasts that are comparable in skill to the multi-model consensus and official track forecasts (Fig. 2).

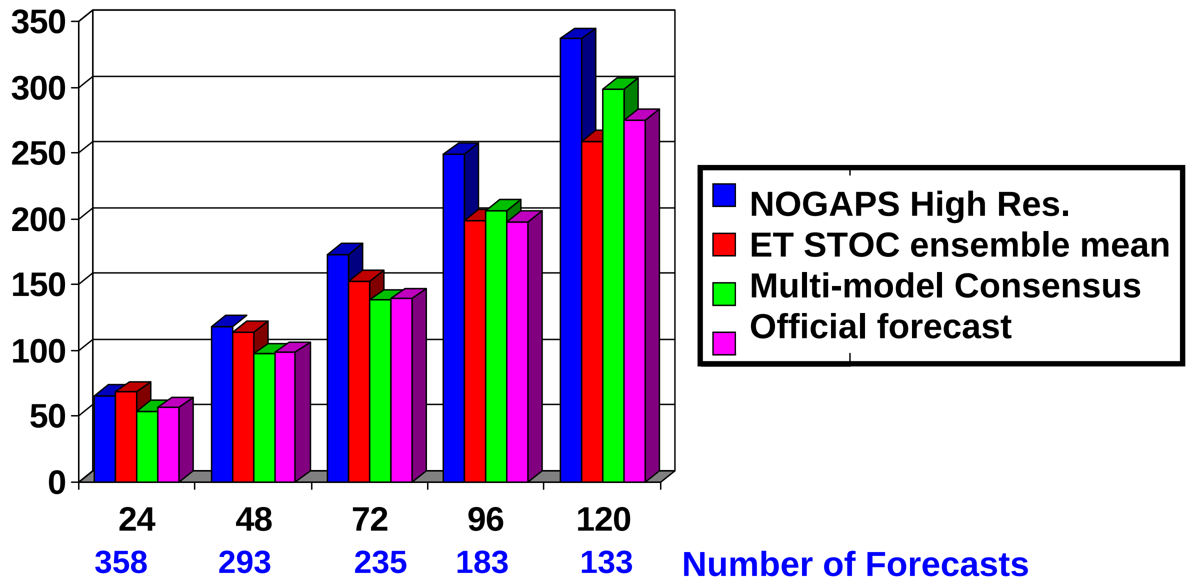

Fig. 2. Average forecast error (nm) for the 2005 Atlantic Hurricane season as a function of forecast lead time. The ET Stochastic ensemble (red) at 96 and 120 hours is comparable in skill to the multi-model consensus (green) and official (pink) forecasts.

For the mesoscale ensemble system, the 29-member COAMPS 48-h forecasts for the 45-km CONUS domain for three weeks (25 June to 17 July 2005) has been used to develop new perturbed physics parameters and new post-processing software. Rank histograms (or Talagrand diagrams) show the rank frequency of observations relative to the ensemble forecasts, and are a useful tool to evaluate the reliability of probabilistic forecasts. Fig. 3 shows the Talagrand diagram for the 29-member COAMPS CONUS case for 850-hPa u-wind component, v-wind component, and air temperature. Thirty ranks are shown because the unperturbed control member is included in the analysis. To account for the effect of radiosonde observation error, random numbers with standard deviation equal to estimated observation error variance (1.9 m s^{-1} for u- and v- wind components and 1^{o}C for air temperature) are added to each of the forecasts before the histogram was formed. Forecasts are adjusted by adding a bias correction constant equal to the 21-day mean of the observation minus the forecast (0.3 m s^{-1} for u and v, and 0.6^{o}C for air temperature).

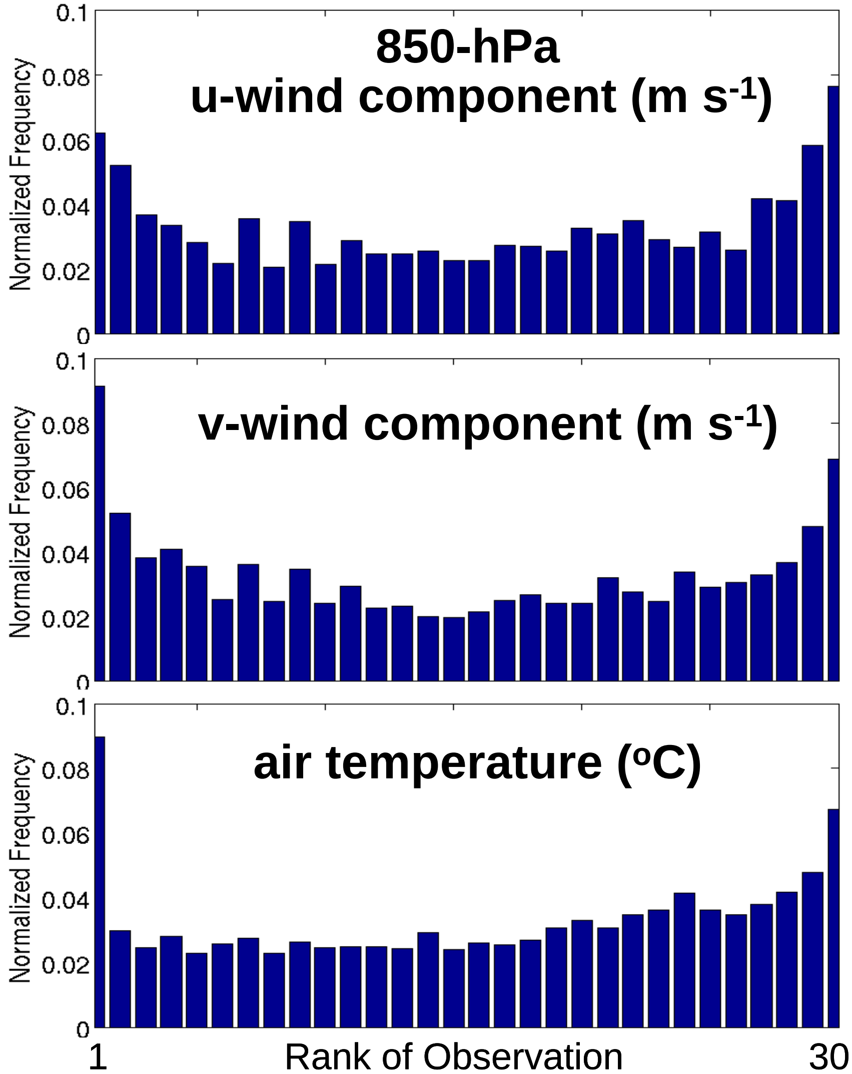

Fig. 3. Rank frequency of observations relative to the ET ensemble (Talagrand diagram) for COAMPS 48-h ensemble forecasts for the 45-km CONUS domain from 25 June to 17 July 2005.

Two additional experiments, termed version 1 (v1) and version 2 (v2) were conducted in which perturbations to the COAMPS planetary boundary layer (PBL), surface layer, microphysical, and cumulus physical parameterizations were included along with the ET. For the 28 v1 perturbation members of the ensemble, the perturbations included: 3 PBL, 2 surface flux, 2 microphysics, 13 cumulus, 7 PBL/surface flux/cumulus combination, and 1 PBL/surface flux combination. For this perturbation set, while the skill of the ensemble as represented by the spread-skill relationship was improved with perturbed parameters (as compared to the control), some members exhibited extreme errors. This is illustrated in precipitation error metrics shown in Fig. 4. To address this deficiency, the initial v1 perturbations are tuned to eliminate members with unrealistically large statistics and new modified members for physical parameterization perturbations (v2) are developed. The v2 ensemble performance is generally improved over v1 (Fig. 4 right panels), and the ensemble mean is more skillful than the control, particularly for v2.

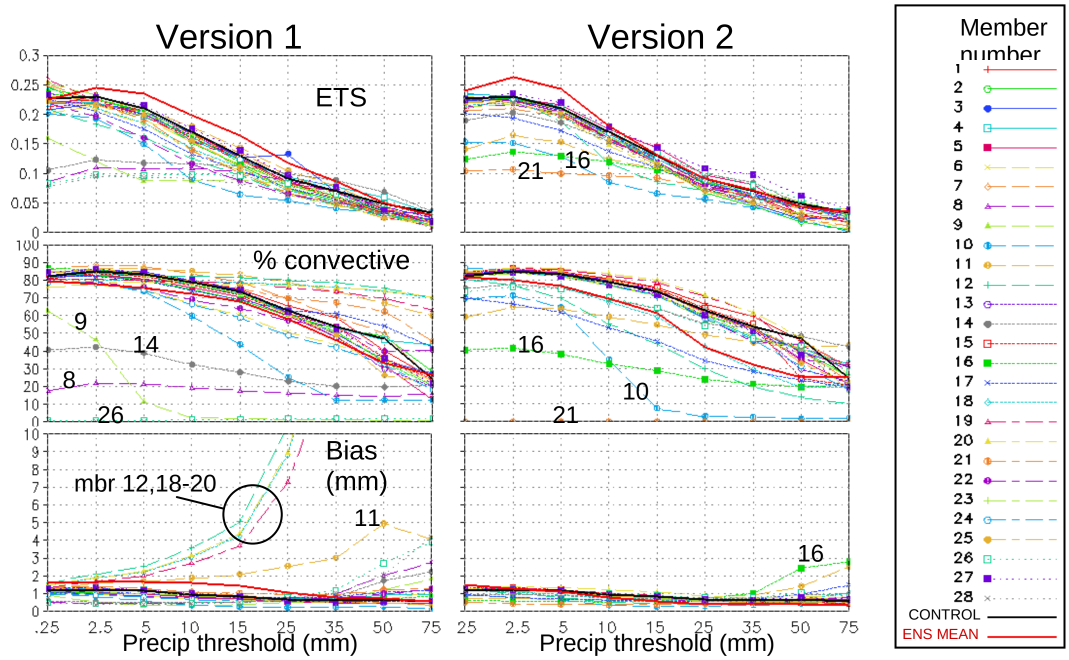

Fig. 4. The COAMPS 48-h ensemble precipitation forecasts for the 45-km CONUS domain from 25 June to 17 July 2005 for the version 1 (v1) perturbations (left panels) and version 2 (v2) (right panels) of equitable threat score (ETS) (top), percentage of points that are convective (middle), and bias (mm) (bottom). The numbers in the plots represent member number, and the thick black line is the control and the thick red line is the ensemble mean.

Fig. 5 shows the spread-skill relationship for precipitation for the v1 and v2 perturbation ensembles. Note that the v1 ensemble attained a larger spread (over-dispersive), but the relation to the error variance was not as useful. The spread associated with the v2 ensemble was a much better predictor of error.

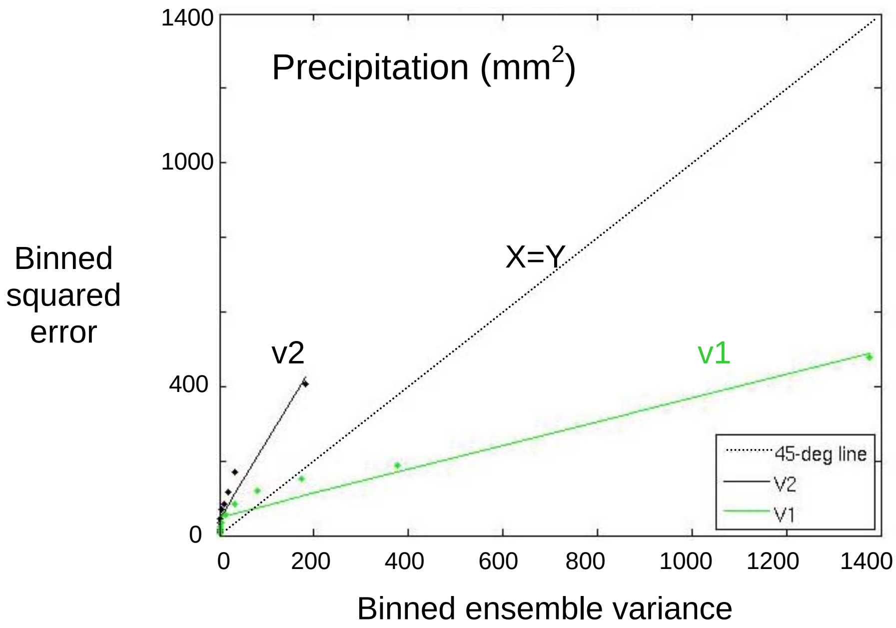

Fig.5. Ensemble spread-forecast error relationship for precipitation for v1 and v2 perturbed physics.

IMPACT/APPLICATIONS

Since results indicate improved performance of the global ET system over the previous operational method under a variety of metrics, this new scheme is resulting in more skillful global ensemble forecasts for the Navy. This should have a direct impact on current and planned ensemble-based products, such as the probability of gale-fore winds, as well as other products that are currently forced by the global ensemble, or will be in the future, including the mesoscale atmospheric ensembles, and surface ocean wave ensembles. In the future, it is hoped that these more skillful probabilistic tools will lead to more applications of probabilistic forecasts in the DoD, including ship and air routing applications.

TRANSITIONS

Based on the superior performance of the ET as compared to the previously-operational bred-vector scheme, the ET scheme was transitioned to the operational global ensemble system in March 2008. It is anticipated that the stochastic physics and alternative basis improvements will be transitioned through 6.4 to operations sometime in FY09. In addition, as part of the Navy/Air Force Joint Mesoscale Ensemble (JME) ensemble forecasting project we have aided FNMOC in the set up, and running of a “beta-ops” real time ensemble forecasting system over the Korean peninsula. The COAMPS ET ensemble has been running continuously on the HPC DC3 system since late June 2008. The transition to operations is in progress, with porting to the FNMOC OPAL A2 system underway.

RELATED PROJECTS

The global ET and Stochastic Physics research began in preceding years under the NRL base-funded project 6.1-Quantifying Limits of Atmospheric Predictability and the NOAA funded project 6.2 Stochastic Physics. In addition, research under the NRL base-funded project 6.2-Model Discovery, which uses ensembles to understand model behavior within parameter space, will lead to methods to perturb parameters in ensembles and be transitioned to operations through this work unit in FY09.

For the mesoscale ensemble development related projects include ONR funded 6.2-Probabilistic Forecasting of High Impact Weather, 6.2-Hidden Volatility in Environmental State Estimation, and 6.1-Quantifying Limits of Atmospheric Predictability. The research is also related to the NOAA funded projects 6.2 Stochastic Physics and 6.2 Huge Ensemble State Estimation.

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